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Nuclear Energy Levels of Cr^{52}, Mn^{55}, and Zn^{66}†

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Nuclear energy levels of Cr^{52}, Mn^{55}, and Zn^{66} have been determined by analyses of particles from the $Cr^{52}(p,p')Cr^{52}$, $Mn^{55}(p,\alpha)Cr^{52}$, $Mn^{55}(p,p')Mn^{55}$, $Zn^{66}(p,p')Zn^{66}$, and $Ga^{69}(p,\alpha)Zn^{66}$ reactions with a broad-range single-gap magnetic spectrograph. In the first 6.3 MeV of excitation energy, 66 levels of Cr^{52}; in the first 3.9 MeV, 62 levels of Mn^{55}; and in the first 4.8 MeV, 74 levels of Zn^{66} were resolved and investigated.

INTRODUCTION

As part of a general investigation of level densities by various methods, the energies of excited levels of Cr^{52}, Mn^{55}, and Zn^{66} were measured by high-resolution magnetic analyses of particles emitted in the $Cr^{52}(p,p')$, $Mn^{55}(p,\alpha)$, $Mn^{55}(p,p')$, $Zn^{66}(p,p')$, and $Ga^{69}(p,\alpha)$ reactions.

Low-lying levels of Cr^{52} have been investigated previously by studying the decay of Mn^{52}.[1,2] In addition, some twenty levels of Cr^{52} were studied by the $Cr^{52}(p,p')$ [3] and $Mn^{55}(p,\alpha)$ reactions.[4] Levels of Mn^{55} have been studied previously by magnetic analysis of protons.[5] Several low-lying levels in Zn^{66} have been identified with very good accuracy by studying the γ rays of Ga^{66} with a lithium-drifted germanium detector.[6]

In the present work, 66 levels were resolved up to an excitation energy of 6.3 MeV in Cr^{52} and 74 levels were resolved up to an excitation energy of 4.8 MeV in Zn^{66}. Two different reactions were used for the determination of energy levels of Cr^{52} and Zn^{66} in order to reduce the probability of missing levels. In addition, 62 energy levels of Mn^{55} were investigated by inelastic proton scattering in the excitation energy range 0–3.9 MeV.

EXPERIMENTAL PROCEDURE

The measurements were made with the Argonne tandem Van de Graaff and broad-range single-gap magnetic spectrograph.[7] Measurements were made for each reaction at different angles and projectile energies. A summary of this information is given in Table I.

† Based on work performed under the auspices of the U. S. Atomic Energy Commission.

[1] R. R. Wilson, A. A. Bartlett, J. J. Kraushaar, J. D. McCullen, and R. A. Ristinen, Phys. Rev. **125**, 1655 (1962).

[2] M. S. Freedman, F. Wagner, Jr., F. T. Porter, and H. H. Bolotin, Phys. Rev. **146**, 791 (1966).

[3] K. Matsuda, Nucl. Phys. **33**, 536 (1962).

[4] E. Veje, C. Droste, O. Hansen, and S. Holm, Nucl. Phys. **57**, 451 (1964).

[5] M. Mazari, A. Sperduto, and W. W. Buechner, Phys. Rev. **108**, 103 (1957).

[6] M. S. Freedman, F. T. Porter, and F. Wagner, Jr., Phys. Rev. **151**, 899 (1966).

[7] C. P. Browne and W. W. Buechner, Rev. Sci. Instr. **27**, 899 (1956).

Targets of chromium[8] enriched to 99.9% in Cr^{52}, zinc[7] enriched to 99.9% in Zn^{66}, and 99% pure manganese were prepared by vacuum evaporation onto carbon-backing foils of 20–35 $\mu g/cm^2$ thickness. Isotopically pure targets of Ga^{69} were prepared with the Argonne isotope separator.[9]

Nuclear emulsion plates (Kodak NTA) of 50-μ thickness were used for recording the proton spectra, and Ilford KO plates of 50-μ thickness were used for the α-particle spectra. By proper development, proton and deuteron tracks were suppressed in the plates used for determination of α particles. On each plate, reference lines were marked at accurately known positions prior to exposure, and all measurements were made with respect to these reference lines. Measurements were made of the number of particles in consecutive strips which were 0.5 mm wide and 10 mm long. According to the calibration used, the projection on the baseline of a point of $\frac{1}{3}$ maximum height on the high-energy side of a peak was taken as the position of the corresponding particle group. The calibration of Erskine,[10] based on a value of 5.3045 MeV for the α particles of

TABLE I. List of reactions studied with magnetic spectrograph.

Reaction	Projectile energy (MeV)	Angle (lab) in degrees	Target thickness ($\mu g/cm^2$)	Excitation energy in MeV up to which levels were resolved
$Cr^{52}(p,p')Cr^{52}$	8.97	90	20	5.5
	9.97	140	20	5.0
	10.96	140	20	6.3
	11.96	120	20	6.3
$Mn^{55}(p,\alpha)Cr^{52}$	11.96	90	10	6.3
	11.96	120	10	6.2
$Mn^{55}(p,p')Mn^{55}$	7.98	140	20	3.9
	9.97	120	20	3.4
	8.97	60	20	3.5
	8.97	140	20	3.8
$Zn^{66}(p,p')Zn^{66}$	11.00	100	30	4.8
	11.00	130	30	4.8
$Ga^{69}(p,\alpha)Zn^{66}$	10.00	140	5	4.4

[8] The enriched isotopes were purchased from the Isotopes Division of Oak Ridge National Laboratory, Oak Ridge, Tennessee.

[9] We are indebted to J. L. Lerner for his preparation of the Ga^{69} target.

[10] J. Erskine (private communication).

TABLE II. Energy levels of Cr^{52} and particle group intensities, averaged from four $Cr^{52}(p,p')Cr^{52}$ and two $Mn^{55}(p,\alpha)$ experiments with the magnetic spectrograph.

Level	Excitation energy (MeV) This work		Freedman *et al.*[a]	Intensity[b] $Cr^{52}(p,p')$	$Mn^{55}(p,\alpha)$	Spin[a]
0	0.000		0.000		0.1	0^+
1	1.434	±0.005	1.435	3.0	1.0	2^+
2	2.371	±0.005	2.370	1.1	1.5	4^+
3	2.650	±0.005	2.648	0.5	0.1	0^+
4	2.767	±0.005	2.769	1.1	1.4	4^+
5	2.965	±0.005	2.965	1.3	1.0	2^+
6	3.114	±0.005	3.115	0.4	0.9	6^+
7	3.163	±0.005	3.161	1.6	0.8	2^+
8	3.416	±0.005	3.415	0.9	1.0	
9	3.472	±0.005		1.4	1.0	
10	3.619	±0.005	3.618	0.5	1.2	5^+
11	3.772	±0.005		1.5	0.7	
12	3.947	±0.005		0.6	0.9	
13	4.016	±0.005		0.3	0.9	
14	4.040	±0.005		0.7	1.1	
15	4.563	±0.005		1.2	0.8	
16	4.630	±0.005		0.9	1.4	
17	4.706	±0.005		1.4	0.6	
18	4.743	±0.005		1.3	1.2	
19	4.808	±0.005		0.4	0.7	
20	4.837	±0.005		0.9	1.0	
21	4.950	±0.005		0.8	0.5	
22	5.097	±0.005		1.2	1.4	
23	5.141	±0.005		0.2	0.8	
24	5.211	±0.005		0.5	0.3	
25	5.281	±0.005		0.3	0.7	
26	5.346	±0.005		0.5	0.7	
27	5.410	±0.005		1.4	1.3	
28	5.422	±0.008		0.4	0.4	
29	5.432	±0.008		0.8	1.3	
30	5.450	±0.006		1.0	0.6	
31	5.494	±0.005		0.8	0.7	
32	5.538	±0.005		1.1	0.4	
33	5.546	±0.008		0.8	0.4	
34	5.571	±0.005		1.3	1.1	
35	5.585	±0.007		0.5	0.1	
36	5.664	±0.005		0.9	0.5	
37[c]	5.725	±0.005		0.7	1.1	
38	5.798	±0.005		0.4	0.5	
39	5.812	±0.008				
40	5.816	±0.008		0.5		
41	5.853	±0.005		1.0		
42	5.866	±0.007		1.0		
43	5.879	±0.006		1.1		
44	5.916	±0.006		0.6		
45	5.922	±0.010		0.6		
46	5.953	±0.006		0.7		
47	5.960	±0.007		1.0		
48	5.996	±0.006		0.4	0.7	
49	6.026	±0.007				
50	6.035	±0.010				
51	6.057	±0.007				
52	6.065	±0.010				
53	6.107	±0.007				
54	6.145	±0.007				
55	6.155	±0.012				
56	6.164	±0.012				
57	6.175	±0.010		0.8		
58	6.192	±0.008		0.8		
59	6.205	±0.006				
60	6.210	±0.010				
61	6.220	±0.008				
62	6.233	±0.010		0.5		
63	6.253	±0.008		0.3		
64	6.272	±0.008		0.3		
65	6.282	±0.010		0.3		
66	6.294	±0.010		0.3		

[a] Reference 2.
[b] Intensity relative to the average of levels 4–12.
[c] Doublet.

TABLE III. Energy levels of Mn^{55} and particle group intensities, averaged from four (p,p') experiments.

Level	Excitation energy (MeV) This work		Mazari *et al.*[a]	Intensity[b]	Spin
0	0.000				$\frac{5}{2}^-$
1	0.124	±0.002[c]	0.127	4.2	$\frac{7}{2}^-$
2	0.982	±0.002	0.983	1.7	
3	1.290	±0.002	1.289	1.0	
4	1.526	±0.002	1.527	1.0	
5	1.883	±0.002	1.884	1.0	
6	2.197	±0.002	2.197	1.0	
7	2.251	±0.002	2.252	1.1	
8	2.266	±0.002	2.266	0.6	
9	2.281	±0.010	2.288	0.7	
10	2.311	±0.002	2.311	0.4	
11	2.365	±0.002	2.365	1.3	
12	2.398	±0.002	2.397	1.0	
13	2.425	±0.002	2.426	0.4	
14	2.564	±0.002	2.564	1.0	
15	2.582	±0.005	···	0.4	
16	2.726	±0.002	2.727	1.0	
17	2.751	±0.002	2.751	0.8	
18	2.823	±0.002	2.823	1.0	
19	2.874	±0.005	2.874	5.0	
20	2.954	±0.002	2.953	1.0	
21	2.975	±0.002	2.976	0.5	
22	2.990	±0.002	2.991	0.6	
23	3.004	±0.002	3.005	0.9	
24	3.037	±0.005	3.037		
25	3.045	±0.005	···		
26	3.050	±0.005	···	0.7	
27	3.081	±0.002	3.081	0.7	
28	3.129	±0.002	3.124	0.6	
29	3.160	±0.002	3.156	0.7	
30	3.195	±0.002	3.195	0.8	
31	3.261	±0.005	3.263		
32	3.270	±0.005	···		
33	3.342	±0.002	.3403	0.7	
34	3.351	±0.002	3.351	1.0	
35	3.374	±0.005	3.371	0.3	
36	3.379	±0.008	3.378		
37	3.385	±0.008	···		
38	3.424	±0.005	3.424	0.4	
39	3.432	±0.005	···		
40	3.480	±0.010[d]	···	0.2	
41	3.505	±0.010[d]	···	0.3	
42	3.523	±0.005	···	0.4	
43	3.528	±0.005	3.529	0.6	
44	3.580	±0.002	3.587	0.9	
45	3.597	±0.005	···		
46	3.604	±0.005	3.607		
47	3.611	±0.005	···	0.7	
48	3.631	±0.010	···	0.25	
49	3.642	±0.010	···	0.15	
50	3.661	±0.005	3.660	0.46	
51	3.673	±0.010	···	0.2	
52	3.682	±0.010[d]	···	0.2	
53	3.702	±0.002	3.706	0.7	
54	3.752	±0.002	···	0.6	
55	3.772	±0.002	3.775	0.6	
56	3.791	±0.002	3.796	0.7	
57	3.800	±0.005	···	0.2	
58	3.832	±0.005	3.832	0.4	
59	3.842	±0.005	···	0.3	
60	3.860	±0.005	3.862	0.6	
61	3.883	±0.005		0.4	
62	3.915	±0.005		0.5	

[a] Reference 5.
[b] Intensity relative to the average intensity of levels 2–12.
[c] See footnote c in Table IV.
[d] These levels are somewhat uncertain and not positively identified.

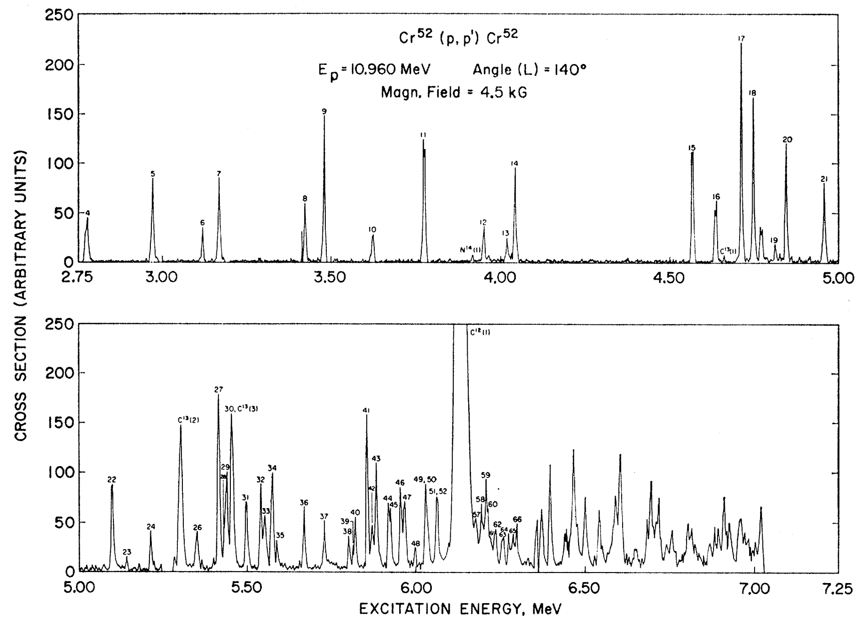

FIG. 1. Spectrum of protons inelastically scattered from Cr^{52}.

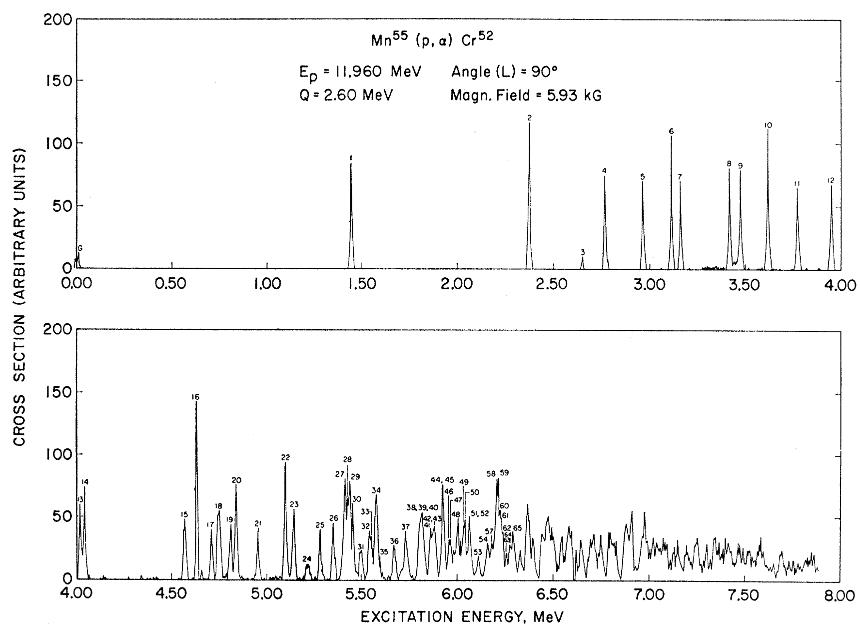

FIG. 2. Spectrum of α particles from the reaction $Mn^{55}(p,\alpha)Cr^{52}$.

Po^{210}, was used. In addition, the accuracy and reproducibility of this calibration was checked by observing the positions of the second and third excited levels of C^{13} in all (p,p') runs. The energy of the second-excited level of C^{13} has been very accurately measured[11] to be 3.684_3 MeV. Comparison of the experimental energies of the two levels in C^{13} for the (p,p') runs with energy values in the literature indicate a possible error of ± 0.004 MeV in the calibration.

Half-widths of 6–8 keV were observed for the proton groups and about 10–15 keV for the α-particle groups (see Figs. 1–4). The poorer resolution for the α-particle groups is partly because of their higher energy loss and straggling in the target. Most of the increase in half-width for the α particles, however, is probably owing to the fact that—because of their larger Coulomb barrier—these particles were observed at higher energies than the protons. Since the relative energy resolution $\Delta E/E$ of the spectrograph is approximately independent of the energy E, the linewidth ΔE for the α particles is larger.

The Q value of each of the various particle groups

[11] R. E. Carter and H. T. Motz, Argonne National Laboratory Report No. ANL-6797, 1963, p. 179 (unpublished).

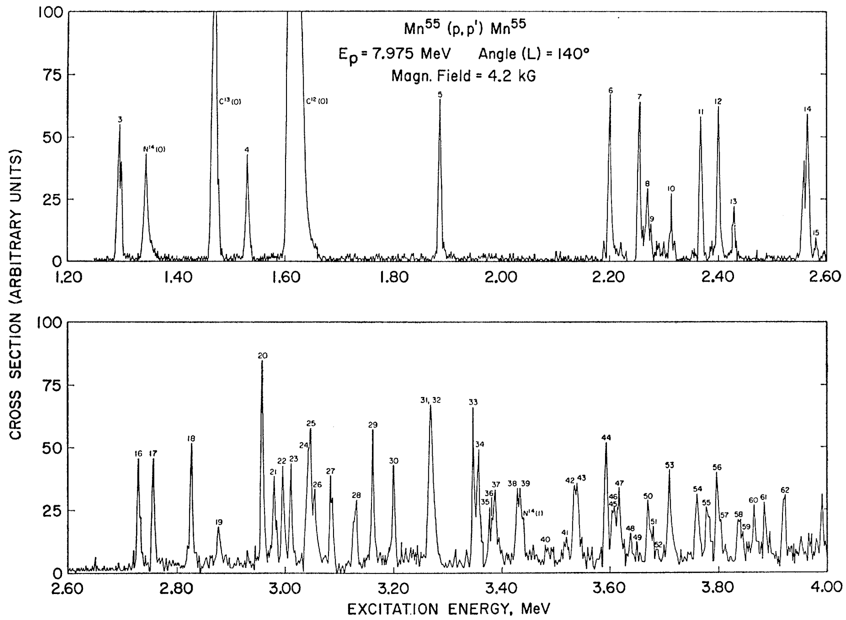

FIG. 3. Spectrum of protons inelastically scattered from Mn^{55}.

on the plates was calculated with the Argonne CDC 3600 computer. Relativistic kinematics were used in the transformation program.

RESULTS

Typical spectra of the particles from the various reactions are shown in Figs. 1–4. In some of the (p,p') reactions the energy scale was expanded on the spectrograph in order to improve the resolution in the higher excitation-energy range; as a consequence some well-known low-excitation-energy groups fell outside the spectrograph range.

The energies of the excited levels of Cr^{52} are listed in column 2 of Table II. These values were obtained by averaging four $Cr^{52}(p,p')$ and two $Mn^{55}(p,\alpha)$ experiments (see Table I). The energies and spin of levels 1–8 and level 10 determined by Freedman *et al.*[6] are listed in columns 3 and 6, respectively, of Table II. The intensities of the particle groups for each of the two different reactions were calculated relative to the average of the intensities of levels 4–12 and these data are given in columns 4 and 5 of Table II. Averaging of the intensities over the individual (p,p') and (p,α) experiments was performed because the expected Ericson fluctuations were comparable to the differences of individual runs which were carried out at different angles and bombarding energies.

The average energies of the excited levels of Mn^{55} determined from four (p,p') experiments (see Table I) and the intensities of the corresponding proton groups are listed in Table III. The average energies of the excited levels of Zn^{66} determined from two (p,p') experiments and one (p,α) experiment along with the corresponding particle intensities are given in Table IV. The ground-state Q values for the $Mn^{55}(p,\alpha)Cr^{52}$ and $Ga^{69}(p,\alpha)Zn^{66}$ reactions were found to be 2.60 ± 0.01 and 4.44 ± 0.01 MeV, in comparison to 2.570 and 4.419 MeV, respectively, given in the 1964 atomic mass table.[12]

[12] J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. **67**, 1 (1965).

Systematic and random errors arise in the determination of level energies. Systematic errors are due to the limited accuracy and reproducibility of the calibration, and in this experiment are probably less than 4 keV. Random errors are introduced due to the statistical uncertainty involved in the determination of the position of the particle groups. For well-separated groups of average intensity the random error is expected to be 2 keV, whereas for partially overlapping groups, the random error might be as large as 8 keV.

As can be seen in Tables II and IV, the agreement in energy between the low-lying levels of Cr^{52} and Zn^{66} investigated by γ-ray spectroscopy[2,6] with lithium-drifted germanium detectors and our measurements is extremely good. For each of these nuclei we resolve some sixty additional levels. Earlier studies of the $Cr^{52}(p,p')$[3] and $Mn^{55}(p,\alpha)$[4] reactions identified the energies of about twenty levels of Cr^{52}. In addition to resolving many levels at higher excitation energy, we find that several levels were missed in the earlier experiments. The energy levels of Mn^{55} determined in our experiments are compared to earlier results[5] in Table III. The agreement is satisfactory, since the deviations are well within the stated limits of error. Within the energy range investigated in the earlier experiments, eighteen new levels were found in the present experiment although a few of the new levels are not firmly established.

The total number of levels $N(U)$ at excitation energy U is plotted as a function of U in Fig. 5 for Cr^{52}, Mn^{55}, and Zn^{66}. The quantity $N(U)$ is defined by

$$N(U')=\int_0^{U'}\rho(U)dU\,, \qquad (1)$$

where $\rho(U)$ is the level density or number of levels per MeV at excitation energy U. Ericson[13] has defined a temperature τ by the expression

$$1/\tau=d\ln N(U)/dU\,. \qquad (2)$$

[13] T. Ericson, Nucl. Phys. **11**, 481 (1959).

TABLE IV. Energy levels of Zn^{66} and particle group intensities, averaged from two $Zn^{66}(p,p')$ and one $Ga^{69}(p,\alpha)$ experiment with the magnetic spectrograph.

Level	Excitation energy (MeV) This work		Freedman *et al.*[a]	Intensity[b] $Zn^{66}(p,p')$	Intensity[b] $Ga^{69}(p,\alpha)$	Spin[a]
0	0				0.3	0^+
1	1.041	±0.002[c]	1.0393	15.1	1.3	2^+
2	1.871	±0.002	1.8728	1.3	1.2	2^+
3	2.371	±0.002	2.3723	0.7	0.2	0^+
4	2.450	±0.002		1.1	1.8	
5	2.704	±0.002		0.7	1.1	
6	2.766	±0.002		1.0	0.8	
7	2.778	±0.002	2.783[d]	1.2	0.9	
8	2.828	±0.002		6.1	0.9	
9	2.941	±0.002		0.9	0.7	
10	3.080	±0.002		0.7	0.9	
11	3.107	±0.002[e]		0.3	0.1	
12	3.215	±0.005			0.7	
13	3.225	±0.005			0.4	
14	3.230	±0.005	3.2294	0.6	0.3	$1^\pm$
15	3.332	±0.002[e]		0.7	0.7	
16	3.382	±0.002	3.3812	0.3	0.4	$1^\pm$
17	3.433	±0.002	3.433	0.9	0.7	
18	3.509	±0.002	3.511	0.7	0.9	
19	3.522	±0.002			0.7	
20	3.533	±0.005		0.5	0.3	
21	3.578	±0.002		0.8	0.8	
22	3.673	±0.002		1.2	1.3	
23	3.691	±0.002		0.8	0.8	
24	3.712	±0.002		0.3	0.5	
25	3.726	±0.002			0.5	
26	3.739	±0.002				
27	3.747	±0.005				
28	3.752	±0.010				
29	3.794	±0.002	3.7917	0.6	0.4	1^+
30	3.809	±0.002[e]	3.806	0.7	0.7	
31	3.824	±0.005		0.4	0.4	
32	3.874	±0.005				
33	3.881	±0.005				
34	3.901	±0.005		0.9	0.4	
35	3.926	±0.002[e]		0.6	0.7	
36	3.946	±0.002		0.6	1.3	
37	3.969	±0.002		0.4	0.8	
38	4.021	±0.002		0.6	0.7	
39	4.081	±0.002			0.2	
40	4.089	±0.002	4.0862[d]		0.6	1^+
41	4.116	±0.002		2.3	1.9	
42	4.181	±0.002				
43	4.188	±0.010				
44	4.223	±0.002		0.5	0.4	
45	4.258	±0.002				
46	4.265	±0.010				
47	4.295	±0.002	4.2953	0.6	0.2	1^+
48	4.322	±0.002				
49	4.327	±0.010				
50	4.392	±0.002		3.2	1.8	
51	4.425	±0.005	4.427			
52	4.435	±0.010				
53	4.440	±0.010				
54	4.454	±0.005				
55	4.463	±0.010	4.4615			1^+
56	4.470	±0.010				
57	4.496	±0.003				
58	4.511	±0.005				
59	4.527	±0.005				
60	4.535	±0.010				
61	4.565	±0.002				
62	4.610	±0.005				
63	4.620	±0.010				
64	4.636	±0.005				
65	4.645	±0.010				
66	4.658	±0.010				
67	4.683	±0.010				
68	4.693	±0.010				
69	4.730	±0.010				
70	4.745	±0.010				
71	4.758	±0.010				
72	4.782	±0.010				
73	4.798	±0.010				
74	4.807	±0.010	4.8059			1^+

[a] Reference 6.
[b] Intensity relative to the average intensity of levels 2–7.
[c] These small errors are assigned on the basis of the excellent agreement over the whole energy range with the lithium-drifted germanium detector measurements (Ref. 6).
[d] More recent γ-ray measurements give energies of 2.7805 and 4.0880 MeV for these levels (Ref. 15).
[e] Wide peaks which could be doublets.

The nuclear temperature T is given by

$$1/T = d\ln\rho(U)/dU\,, \tag{3}$$

and T is related to τ by the relationship

$$1/T = 1/\tau[1-(d\tau/dU)]. \tag{4}$$

The values of τ for Cr^{52}, Mn^{55}, and Zn^{66} are 1.43, 0.94, and 0.90 MeV, respectively. However, if only the upper 50 levels of Cr^{52} are included, τ is considerably reduced to a value of about 1.2 MeV.

The level density of Cr^{52} was calculated in the excitation-energy region, where levels were not resolved by counting the number of inelastic protons in fixed energy intervals and making the appropriate solid angle corrections. The differential cross-section $d^2\sigma/d\Omega d\epsilon_2$ for the emission of particles b with channel energy ϵ_2, going to a residual nucleus B at excitation energy U_B with level density $\rho(U_B)$, is given by

$$d^2\sigma/d\Omega d\epsilon_2 \propto \rho(U_B)\epsilon_2\sigma_i(\epsilon_2)\,, \tag{5}$$

where the inverse cross section $\sigma_i(\epsilon_2)$ is calculated with an optical-model computer program. Since Eq. (5) is only a proportionality, absolute values of the level density were obtained by normalizing the cross sections in the excitation energy interval 4–5 MeV to nine levels (see Table II). The results from two $Cr^{52}(p,p')$ and two $Mn^{55}(p,\alpha)$ experiments are given in Table V. The average value of the density in each energy interval is given in column 7. The errors are standard deviations calculated from the deviations of the individual values from the average. Listed in column 8 is the level density, in levels per MeV, which is calculated by summing the number of resolved levels per $\frac{1}{2}$-MeV interval from Table II, and multiplying by 2. Possible errors in the level density values of column 8 are due only to unresolved levels. Therefore, these values represent a minimum limit of the level density. The good agreement between the values in columns 7 and 8 in Table V at excitation energies above 5 MeV indicates that the levels were well resolved in this region.

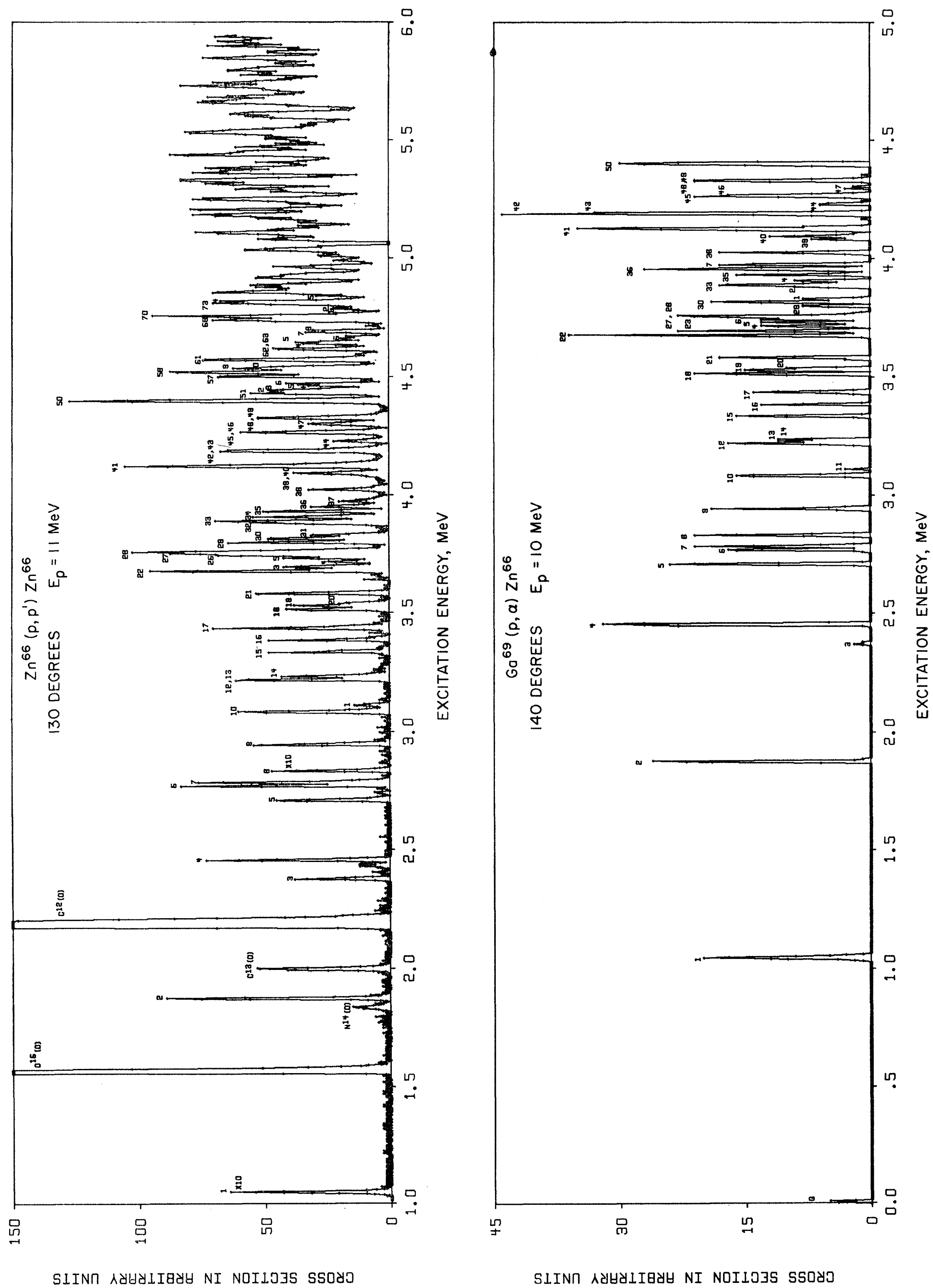

FIG. 4. Top: spectrum of protons inelastically scattered from Zn^{66}. Bottom: spectrum of α particles from the reaction $Ga^{69}(p,\alpha)Zn^{66}$.

TABLE V. Level density of Cr^{52} from the experiments with the magnetic spectrograph; all the densities are given in levels per MeV.

Excitation energy (MeV)	Energy interval (MeV)	Evaporation spectra $Cr^{52}(p,p')$ 120° 12 MeV	$Cr^{52}(p,p')$ 140° 11 MeV	$Mn^{55}(p,\alpha)$ 90° 12 MeV	$Mn^{55}(p,\alpha)$ 120° 12 MeV	Average of columns 3–6	From the No. of levels of Table II
2.75	2.5–3.0	4		3	3	3±1	6
3.25	3.0–3.5	5	6	6	4	5±1	8
3.75	3.5–4.0	5	4	6	4	5±1	6
4.25	4.0–4.5	3	2	4	3	3±1	4
4.75	4.5–5.0	16	16	14	15	15±1	14
5.25	5.0–5.5	20	25	22	21	22±2	20
5.75	5.5–6.0	37	36	35	36	36±1	34
6.25	6.0–6.5	58	54	63	86	65±12	
6.75	6.5–7.0	96	77	86	123	96±17	
7.25	7.0–7.5		92	138	211	147±49	
7.65	7.5–7.8			179	358	269±90	

DISCUSSION

For reactions which proceed through an intermediate compound nucleus, it is possible to calculate their cross sections according to the statistical theory of nuclear reactions. Calculations of the cross sections to isolated final levels have been discussed previously.[14] In Figs. 6 and 7 the results of such statistical theory calculations are displayed for the $Zn^{66}(p,p')$ and $Ga^{69}(p,\alpha)$ reactions. The relative cross section is plotted as a function of the angular momentum of the final level for different residual excitation energies. The relative yields of the $Cr^{52}(p,p')$ and $Mn^{55}(p,\alpha)$ reactions are consistent with the spin assignments given in Table II for several excited levels of Cr^{52}.

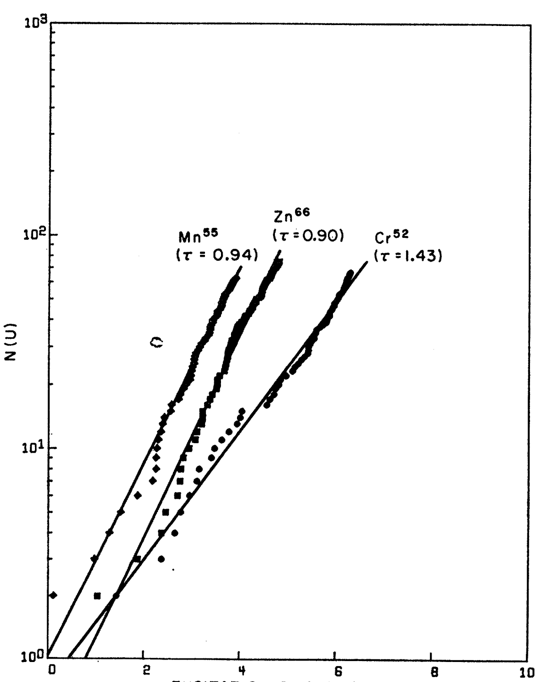

FIG. 5. The total number of levels up to excitation energy U, as obtained from the data of Tables II–IV [see Eq. (1)], plotted as a function of U.

[14] A. A. Katsanos, J. R. Huizenga, and H. K. Vonach, Phys. Rev. **141**, 1053 (1966).

Levels of Zn^{66} have been investigated recently with lithium-drifted germanium detectors.[6] In our experiments we see no evidence of levels at 2.800 and 3.450 MeV. The weak γ-ray lines which were associated with these proposed levels do have other assignments[6] in terms of the levels found in this experiment and we have included these new assignments in column 3 of Table IV. Our level energies agree very well with the data of Freedman *et al.*[6] up to an excitation energy of 4.8 MeV. For 15 levels, the average difference in energy per level is only 0.1 keV. Level No. 7 at 2.778 MeV differs by 5 keV; however, more recent γ-ray measurements[15] reduce this difference by a factor of 2.

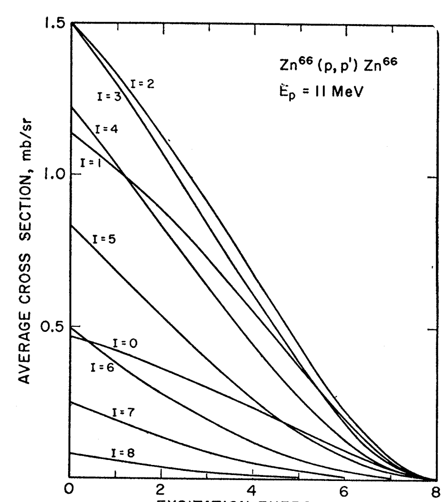

FIG. 6. Statistical theory calculation of the cross section for exciting a level of particular excitation energy and angular momentum in the $Zn^{66}(p,p')$ reaction induced with 11-MeV protons. Although a particular set of parameters was used to give the absolute cross sections on the ordinate scale, these parameters are rather uncertain and in practice the ordinate scale should be understood in terms of relative cross sections only.

[15] David Camp (private communication).

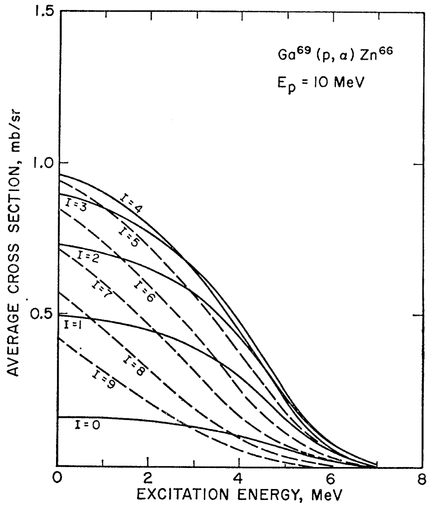

FIG. 7. Statistical theory calculation of the cross section for exciting a level of particular excitation energy and angular momentum in the $Ga^{69}(p,\alpha)Zn^{66}$ reaction induced with 10-MeV protons. The ordinate scale is in terms of relative cross section (see caption of Fig. 6).

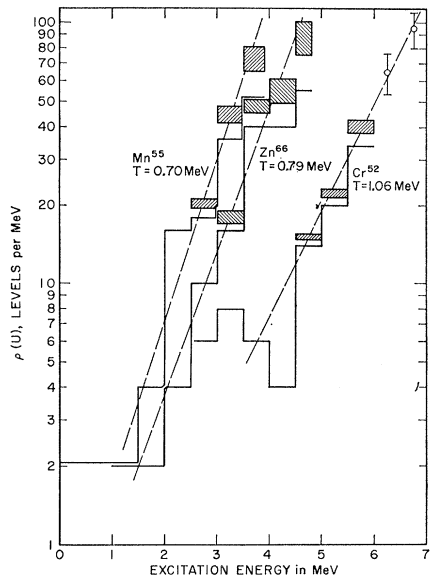

FIG. 8. Level density $\rho(U)$ of Cr^{52}, Mn^{55}, and Zn^{66} as a function of excitation energy. The horizontal lines of the histograms represent the uncorrected level densities determined by direct level counting from the results of these experiments. The cross-hatching represents level densities corrected for unresolved levels. The upper and lower limits to the cross-hatched regions represent upper and lower limits to the corrected level densities according to Eq. (8).

Relative yield measurements favor a spin of 0 over a spin of 2 for the level at 2.371 MeV. The level at 2.828 Mev is strongly excited in the (p,p') reaction and is probably the level assigned by others[16,17] to a collective octupole vibration with spin 3^-.

The level densities $\rho(U)$ in terms of levels per MeV for Cr^{52}, Mn^{55}, and Zn^{66} are plotted in Fig. 8 as a function of excitation energy. The horizontal lines of the histograms represent the uncorrected level densities as determined with the magnetic spectrograph. The two circles are level densities of Cr^{52} from column 7 of Table V.

The distribution of spacings resulting from a random superposition of n unrelated sequences of energy levels has been derived theoretically.[18] For a spin-dependent level density of the form

$$\rho(I)=(2I+1)\rho(0)\exp[-I(I+1)/2\sigma^2] \qquad (6)$$

and levels of both parities with $\sigma \geqslant 2$, one obtains a nearly exponential distribution of level spacings. The exponential distribution is given by

$$P(S/\bar{S})=\exp\{-(S/\bar{S})\}, \qquad (7)$$

and this result has been verified experimentally.[19]

If one estimates from the experimental energy resolution that levels with spacings larger than ΔE_1 are resolved with certainty and levels with spacings smaller than ΔE_2 are unresolved, one obtains for the theoretical level spacing of Eq. (7) the following corrected level-density expression:

$$\rho_{\mathrm{obs}}\exp(\Delta E_2/\bar{S})<\rho_{\mathrm{corr}}<\rho_{\mathrm{obs}}\exp(\Delta E_1/\bar{S}). \qquad (8)$$

In Fig. 8 the uncorrected experimental level density is compared with the level density corrected according to Eq. (8) when ΔE_1 and ΔE_2 are 8 and 4 keV, respectively.

The nuclear temperatures [as defined by Eq. (3)] of Cr^{52}, Mn^{55}, and Zn^{66} were determined from the data of Fig. 8 and these values are 1.06, 0.70, and 0.79 MeV, respectively. The level density of Cr^{52} as a function of excitation energy is very similar to that of Fe^{54}. Both of these nuclei have 28 neutrons and the exponential increase in level density with energy begins above 4 MeV.

[16] H. W. Broek, Phys. Rev. **130**, 1914 (1963).
[17] R. Chaminade, M. Crut, H. Faraggi, D. Garreta, J. Sandinos, and J. Thirion, J. Phys. Radium **22**, 607 (1961).
[18] N. Rosenzweig and C. E. Porter, Phys. Rev. **120**, 1698 (1960).
[19] J. R. Huizenga and A. A. Katsanos, Nucl. Phys. (to be published).